

# Probing the X-ray Variability of Neutron Star LMXBs: the Case of the Brightest Source Sco X-1

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**Abstract.** We have investigated the X-ray variability of Sco X-1 on its normal branch when several simultaneous noise components and quasi-periodic oscillations (QPOs) are observed with the *Rossi* X-ray Timing Explorer (RXTE). The upper kHz QPO frequency is anti-correlated with the X-ray flux on the time scales of the very low frequency noise (VLFN) and the normal branch oscillation (NBO), while the lower kHz QPO strength seems anti-correlated with the NBO flux, opposite to that of the horizontal branch oscillation (HBO). We summarize the overall picture of decomposing the X-ray variability of Sco X-1 on its normal branch into these noise components and QPOs, and discuss the consequences for the X-ray variability models.

## X-RAY VARIABILITY OF NEUTRON STAR LMXBS: WHY SCO X-1 ?

X-ray Variability in neutron star low mass X-ray binaries (LMXBs) has been mostly studied based on the X-ray color-color diagram and the power spectral shape in the Fourier frequency domain (Hasinger & van der Klis 1989). The Fourier power spectra correlates with the energy spectral shape as indicated in the X-ray colors, or the location in the X-ray color-color diagram. Two kinds of sources were classified based on the shape a source tracing out in the color-color diagram. One is the so-called ‘Z’ source, which traces a ‘Z’ shape. The other is the so-called ‘atoll’ source, which traces out an ‘atoll’ shape. The ‘Z’ sources in general can stay in three different spectral states as shown in the color-color diagram – the horizontal branch (HB), the normal branch (NB), and the flaring branch (FB). The ‘atoll’ sources, on the other hand, trace the ‘island’ state, the ‘lower banana’ state, and the ‘upper banana’ state.

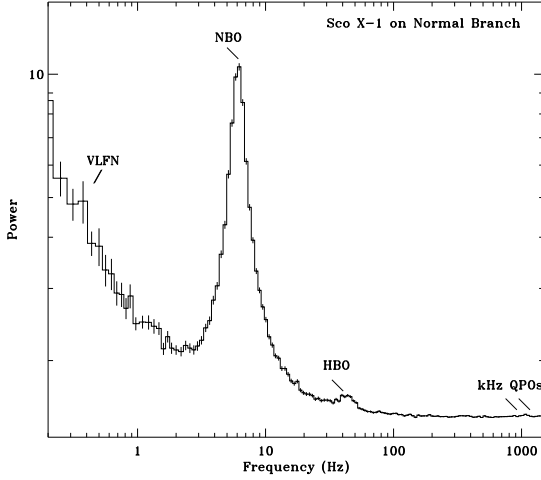
The study of the X-ray variability in neutron star LMXBs depends strongly on the signal-to-noise ratio of a certain X-ray variability component (the ‘noise’ here may include all other variability components that overlaps in frequency with this component). The best observations for the study of a certain quasi-periodic oscillation (QPO) are those when the QPO is detected with high significance. As the QPOs or noise components classified in the ‘Z’ source or ‘atoll’ source generally have similar fractional root-mean-square (*rms*) amplitude among sources on the same branch or state, the best observations for the study of a certain variability component are the observations of the brightest sources in the same branch

or state of the ‘Z’ or ‘atoll’ source group. Sco X-1, the brightest source in the ‘Z’ sources (Hasinger & van der Klis 1989), is one of the best targets because of its high flux.

## DECOMPOSING THE X-RAY VARIABILITY IN FREQUENCY AND TIME DOMAINS

The most successful method in studying the X-ray variability in neutron star LMXBs is the Fourier analysis technique. With the help of Fourier spectral analysis, people have identified and classified signals from LMXBs in the Fourier power spectra, e.g. the very low frequency noise (VLFN), the high frequency noise (HFN), the quasi-periodic oscillations (QPOs), etc (Hasinger & van der Klis 1989). With the help of the *Rossi* X-ray timing explorer (RXTE), kilohertz QPOs have been detected (for a recent review see van der Klis 2000). The decomposing of the X-ray variability in neutron star LMXBs in the Fourier frequency domain is to model the Fourier power spectrum into several noise and QPO components, i.e.  $P_{total}(\nu) = \sum P_i(\nu)$ , where  $P_{total}(\nu)$  is the total power and  $P_i(\nu)$  is the power of the *i*th component at the frequency  $\nu$ . Notice that here we refer to the Fourier power spectra without white noise subtraction, thus the white noise component is one of  $P_i(\nu)$ .

Decomposing the X-ray variability in other domains is clearly possible but not well-studied. One of the main issues related to theoretical interpretation of the X-ray variability is to obtain a time-dependent solution of the



**FIGURE 1.** A typical average Fourier power spectrum of Sco X-1 on its normal branch, consists of VLFN, NBO, HBO and twin kHz QPOs in the frequency range from mHz to kHz.

accretion processes and to compute the radiative transfer which generates the X-rays we observed. This requests a time domain decomposing of the X-ray variability from observational point of view. This problem is basically to decompose the X-ray photon series  $C(t)$  into several additive (independent) or multiplicative (correlated) components  $C_j(t)$ , where  $C_j(t)$  is the X-ray counts at time  $t$  of the  $j$ th component. Here we note frequency domain component with  $i$  and time domain component with  $j$ . Notice that a single time domain component may correspond to several frequency domain components, and vice versa. The direct transformation of the frequency domain components into independent time domain components is probably wrong, as  $C(t)$  is probably not equal to  $\sum C_i(t)$ , because those frequency components may be not independent. This has been confirmed by the study of Sco X-1 on its NB shows that the Fourier spectral components are correlated (Yu, van der Klis & Jonker 2001; Yu & van der Klis 2004).

## SCO X-1 ON NORMAL BRANCH

Sco X-1 is a luminous low mass X-ray binary (Middleditch & Priedhorsky 1986; Priedhorsky et al. 1986; Hertz et al. 1992; Dieters & van der Klis 2000). Its power spectrum on NB and FB are characterized by the normal-branch or flaring branch oscillation (N/FBO) in the frequency range between 6 and 20 Hz with a fractional *rms* amplitude of 1%–5%. According to the interpretation (e.g. Hasinger et al. 1990; Lamb 1991), when the mass accretion rate  $\dot{M}$  to the neutron star increases, the

source moves from the HB to the NB, passes the “vertex” between the NB and FB, where it is thought to reach the Eddington rate, and moves up the FB. Observations have also shown that Sco X-1 stays on its HB with the horizontal oscillation (HBO). Observations of Sco X-1 on its NB before it reaches the “vertex” show the average power spectrum of Sco X-1 composed of most components known in the ‘Z’ sources, i.e. the VLFN, the NBO around 6–8 Hz, a 45 Hz QPO suspected to be HBO, and twin kHz QPO peaks around 800–1100 Hz (van der Klis et al. 1997; Yu, van der Klis & Jonker 2001). Because NBO, HBO and kHz QPOs are simultaneously observed, Sco X-1 on the normal branch is ideal for the study of the relation between those QPOs in ‘Z’ sources.

## VLFN Flux and kHz QPOs

The X-ray count rate on time scales of tens of seconds to hundreds of seconds is an indicator of the VLFN flux of Sco X-1 on its normal branch, as VLFN dominates the X-ray variability on these long time scales. It has been found that there is an anti-correlation between the kHz QPO frequency and the X-ray flux on these time scales (Yu, van der Klis & Jonker 2001). As the kHz QPO frequency has been found to correlate with source location in its X-ray color-color diagram (Wijnands et al. 1998), such an anti-correlation is thought to represent that the X-ray flux on these time scales is anti-correlated with the mass accretion rate through the accretion disk. Thus the X-ray flux variability associated with the VLFN on these long time scales are associated with the mass accretion variation.

## NBO Flux and kHz QPOs

NBO dominates the Fourier power in the 2–16 Hz frequency range. Other components at this frequency range are Poisson noise and a very low amplitude VLFN component. Thus the variation of the X-ray count rate on time scales between 0.25 and 0.03 seconds, which corresponds to 2 and 16 Hz, respectively, represents the NBO flux variation. By selecting time intervals corresponding to the NBO flux local maxima and minima, the kHz QPOs are found to correlate with the NBO flux (Yu, van der Klis & Jonker 2001). Our results show that the upper kHz QPO frequency is anti-correlated with the NBO flux; the upper kHz QPO frequency is found to move at least 22 Hz back and forth within an NBO cycle. Our results also show that the lower kHz QPO strength is anti-correlated with the NBO flux; the lower kHz QPO does not appear when the NBO flux is at its maxima. The slope of correlation indicated in the plot of the kHz QPO fre-

quency vs. the NBO flux is different from that in the plot of the kHz QPO frequency vs. the VLFN flux. This probably indicates a difference between NBO and VLFN in origin.

## NBO Flux and HBO

Similar to the study of the NBO flux vs. the kHz QPO frequency and amplitude, Yu & van der Klis (2004) also show that the 45 Hz HBO amplitude is correlated with the NBO phase or flux. They found that the 45 Hz HBO is consistent with a disappearance when the NBO flux is at minima. The result indicates that the 45 Hz HBO amplitude is correlated with the NBO flux.

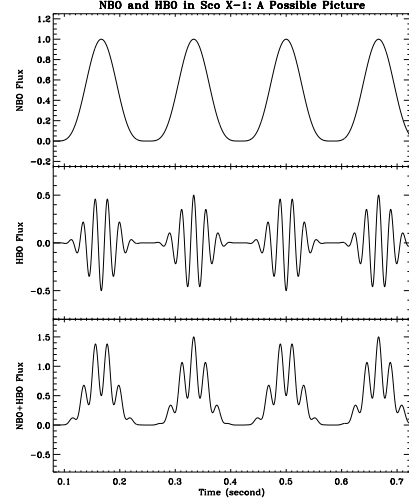
A schematic picture of the correlations among the VLFN, the NBO, the HBO and the kHz QPOs is shown in Fig. 2 and Fig. 3. In summary, the X-ray variability of Sco X-1 on normal branch shows both *frequency-modulated and amplitude-modulated* X-ray QPOs. The properties of the X-ray variability in Sco X-1 on its normal branch are:

- An anti-correlation between the X-ray flux and the upper kHz QPO frequency as well as an anti-correlation between the NBO flux and the upper kHz QPO frequency; the frequency drift on the NBO time scale is comparable to the overall upper kHz QPO width.
- Relative strength variation of the twin kHz QPO peaks in the Fourier power spectrum relative to the NBO flux. HBO strength is also correlated with the NBO flux.
- Frequency separation between the twin kHz QPO peaks is strongly affected by the relative strength variation and frequency drift; This can contribute to 22 Hz systematic uncertainty of the measurement of the frequency separation.

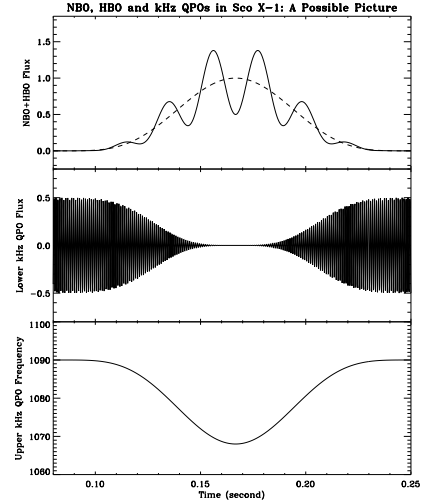
## DISCUSSION

The correlation among the VLFN, the NBO, the HBO and the kHz QPOs implies that the underlying physical parameters of the accretion system in Sco X-1 vary in a way related to these variability modes. This provides important clues to the origin of the X-ray variability in Sco X-1 and sheds light on the overall interpretation of the X-ray variability in the ‘Z’ sources.

If the upper kHz QPO is an indicator of the orbital frequency at the inner edge of the accretion disk, the anti-correlation between the upper kHz QPO frequency and the NBO flux, together with the fact that this anti-correlation is quantitatively different from that formed



**FIGURE 2.** The schematic picture of the composition of NBO and HBO photon count time series for several NBO cycles based on the correlation between the HBO amplitude and the NBO flux. Top panel: NBO oscillation; Middle panel: HBO oscillation; Bottom panel: NBO and HBO together. The fluxes are in arbitrary units.



**FIGURE 3.** The schematic picture of the lower and the upper kHz QPOs during one NBO cycle. The fluxes of the NBO and the HBO are shown in arbitrary units in the top panel. The corresponding lower kHz QPO oscillation is shown in the middle, and the upper kHz QPO frequency is shown in the bottom panel.

for VLFN is probably an evidence of the role of radiative stress from NBO, which is suspected to originate on or close to the neutron star surface, and exert a radiative stress on the inner disk edge (Yu, van der Klis & Jonker 2001). The decreasing strength of the lower kHz QPO with an increasing NBO flux may indicate the failure

of a beat-frequency mechanism to generate the beat-frequency signals when the information of the spin of the neutron star is lost because of the radiative stress's dominating role over that of the magnetic stress. The later carries the neutron star spin information. On the other hand, the correlation between the NBO flux and the strength of the HBO implies that it is possible that the HBO is a modulation of the NBO photons, thus the photons originate from the same geometrical location.

The study of Sco X-1 suggests that the noise or QPO components identified in the Fourier frequency domain are usually related in one way or the other. Several mechanisms can lead to such correlations. For example, a disk variability mode with its amplitude related to the disk mass accretion rate may introduce an amplitude modulated signal. A mode on the neutron star or in boundary layer may modulate the radius of the inner disk edge in an anti-correlation manner. A mode in a spherical corona may incorporate additional modes because of the inverse Comptonization of soft photons from the accretion disk and the neutron star. The details of the correlations to be observed by a larger X-ray timing mission will shed light on the unified description of the X-ray variability in neutron star and black hole X-ray binaries and the probe of the strong field effect using the X-ray variability.

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